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5-Axis Control Finishing for Decreased Tool Wear

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Abstract

With increasing global competition, reduction in the machining cost is the most important issue after machining quality. The machining cost consists of various factors. Among them, the cost of cutting tool holds the first place. The reduction or suppression of tool cost results in an increase in competitive force. This study aims at lengthening the tool life, while decreasing the tool wear. Therefore, the cutting edge of a ball end mill is swung around its center by continuously changing the tool axis vector so that the cutting edge may be uniformly used. Taking account of the width of the flank wear of the ball end mill and the surface roughness of the workpiece in the finishing process, the study proposes an appropriate tool attitude and a suitable tool swing rate of the ball end mill. As a result, the machining method with the tool axis vector continuously swung allows for decreasing tool wear due to its dispersion across the entire tool surface. The proposed method can be applied to machining of workpieces with sculptured faces. From the experimental results, it is found that the proposed idea has the potential of saving tool cost.

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Keywords: 5-axis finishing, tool wear, ball-end mill;

1. Introduction

The global economy has greatly increased competition in manufacturing, thus the machining cost of a product is becoming just as important as the machining quality. Machining cost consists of various factors, among which tooling cost is a major one. It is important to reduce the tool cost for increasing competitiveness. This study aims at lengthening tool life in finishing process for metal mold production by use of ball end mills.

As metal molds often consist of complicated shapes, 5-axis control machining center are often used to process them by use of ball end mills. In order to lengthen tool life, we propose that the tool axis of the ball end mill continuously varies around its center, within a certain angle range and tool swing rate ω. Thus, the tool axis is changed so that the cutting edge may be uniformly used, which results in dispersing the cutting heat generation as well as decreasing the tool wear. There has been prior research to investigate surface roughness when the tool axis is continuously changed [1]. However, such study did not deal with tool wear.

This present study proposes an appropriate tool attitude and a suitable tool swing rate ω to decrease the tool wear. Consequently, the effectiveness is experimentally ascertained by measuring the width of the flank wear and surface roughness of the workpiece.

2. Tool attitude and cutting edge movement

As illustrated in Fig. 1, the tool attitude, equal to a tool axis vector **T**, is defined with the following two angles; the tool axis inclination direction angle α and the tool inclination angle β. The former shows the angle from the tool feed direction around the normal vector **N**, that is, 0 to 360 deg. The latter shows the angle between the normal vector **N** and the tool axis vector **T**.

Figure 2 presents the relationship between the depth of cut t and the tool attitude when the tool axis inclination direction angle α is equal to 270 deg and the tool inclination angle from the normal vector is β. The cutting edge across the ball end mill spans from the point A to the point B, while P_f is the pick feed and r is the tool radius. The angles from the top of ball end mill

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to A and B, are θ_1 and θ_2 respectively, and follow the relationships[2]:

$$\theta_1 = \beta + \cos^{-1}[(r - t) / r]$$
$$\theta_2 = \beta - \sin^{-1}(p_f / 2r)$$

When the tool axis inclination angle β is large, it is expected that tool wear is dispersed across a wider range. However, the cutting edge interferes with the surface to be machined in case $\theta_1 > 90$ deg. Furthermore, in case $\theta_2 < 0$ deg, up-cut and down-cut may exist at the same time within the cutting area.

To avoid this situation, the range of β is set to change between 15 deg and 45 deg with 30 deg being the center, so as to perform the cutting experiments by down-cut only. Thus, $\beta = 30$ deg means that the tool attitude is not swung during machining [3].

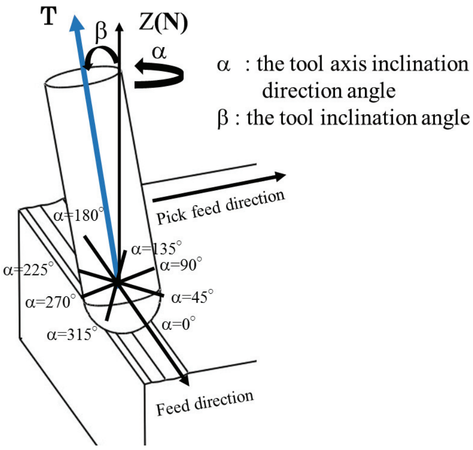


Fig. 1. Definition of tilted tool

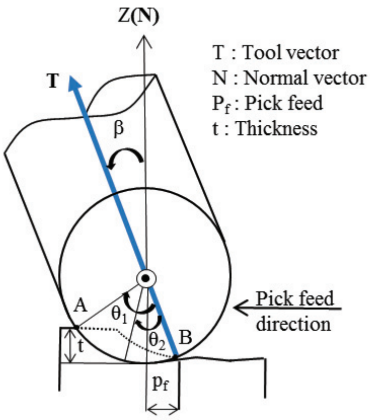


Fig. 2. Tilted tool with $\alpha = 270°$

3. Cutting experiment on plane

The fundamental cutting experiments on a plane are at first planned so that optimum conditions for decreasing the tool wear can be found. Thus, eight tool axis inclination direction angles with regard to α are selected at every 45 deg from the feed direction, as illustrated in Fig. 1, while keeping the tool axis inclination angle $\beta = 30$ deg, that is the tool is no swung. The actual cutting experiment was carried out in the manner shown in Fig. 3.

Measurement of the flank wear was carried out by use of a microscope. The surface roughness of the plane of workpiece was evaluated in the feed direction by use of a surface roughness measuring device, as shown in Fig.4, and with measuring specification shown in Table 1.

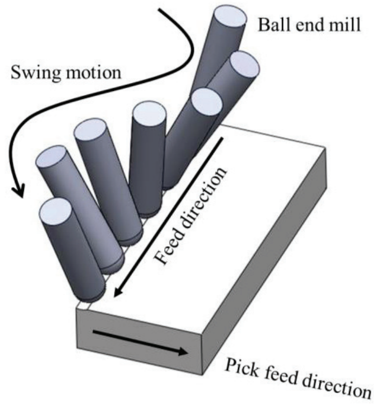


Fig. 3. Swing motion of ball end mill

The experimental conditions are summarized in Table 2. As a hard metal material for the workpiece, SKD61 was selected, such that we could refer to previously published finishing process of metal molds [4,5].This experiment used a 5-axis control machining centre, as shown in Fig.5 and specified in Table 3. Figure 6 shows the radar chart of the tool wear and surface roughness in 8 directions for a cutting length of up-to 15 m, changing the tool swing rate ω between 0, 0.25, and 0.5 deg/mm. Figure 7 and Figure 8 are for cutting lengths of up-to 30 m and 45 m respectively. From these figures, it can be seen that the continuous change in tool attitude allows decreasing of tool wear in all directions. Besides, it was found that the tool axis inclination direction angle α of 90 deg results in the lowest tool wear and good surface roughness, when tool swing takes place. With regard to the tool swing rate ω from the results of tool wear and surface roughness, it was found that the preferred value is $\omega = 0.25$ deg/mm [6,7].

Fig. 4. Surface roughness measuring machine

Table 1 Measuring machine specification

Model No. : Standard drive unit type SJ – 210 178-560-02		
Measuring range	X axis : 17.5 mm	
	Z axis	Range : 360 μm (-200 μm to +160 μm)
		Range / Resolution : 360 μm / 0.02 μm
Measuring speed : (Measuring) 0.5 mm/s , (Returning) 1 mm/s		

Table 2 Machining conditions

Tool : cemented carbide, AlCrN coating, φ10, 2flute	
Workpiece : SKD61	Dry cutting
Spindle revolution : 10000 min^{-1}	Feed : 1000 mm/min
Pick feed : 0.5 mm	Depth of cut : 0.5 mm
Angle : Angle(α) = (0～315 deg), Angle(β) = (15～45 deg, 30 deg)	
Tool swing rate : ω = 0 deg/mm, 0.25 deg/mm, 0.5 deg/mm	

Fig. 5. Machining center used in the experiment

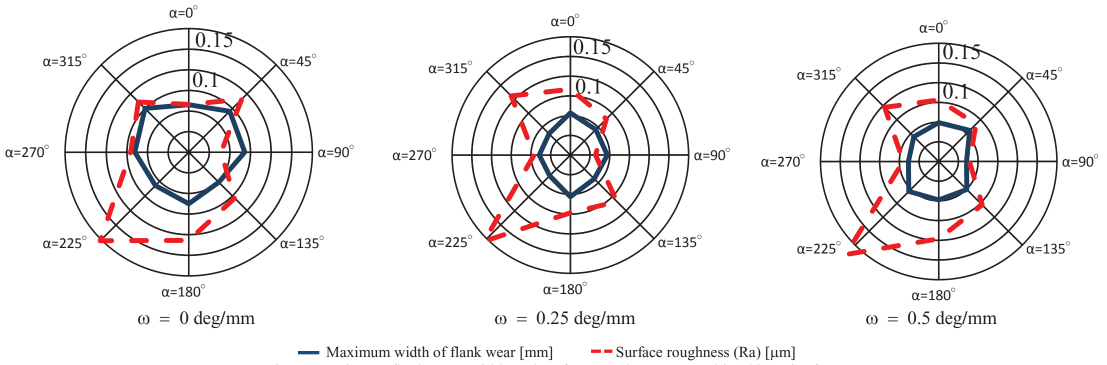


Fig. 6 Maximum flank wear width and surface roughness at machined length of 15m

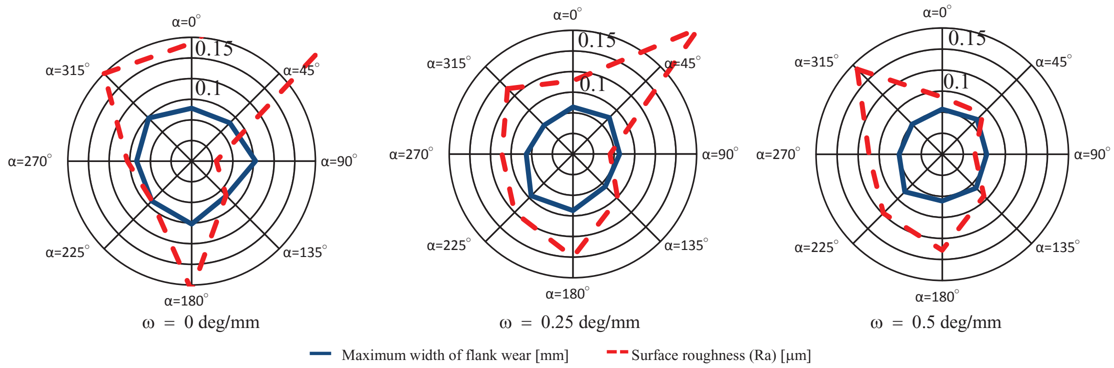


Fig. 7 Maximum flank wear width and surface roughness at machined length of 30m

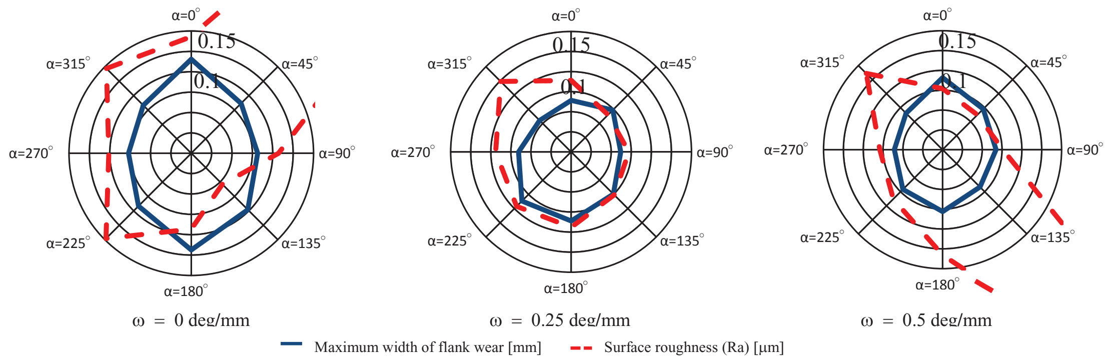


Fig. 8 Maximum flank wear width and surface roughness at machined length of 45m

Table 3 Technical data of DMU50

Main drive	Rotational speed range	20 ～ 14000 rpm
Tool pockets	Number	30
Traverse path	X	500 mm
	Y	450 mm
	Z	400 mm
	B	-5 ~ +110 deg
	C	360 deg

Micrographs of the cutting edge, with and without tool swing, are shown in Fig. 9 and 10.

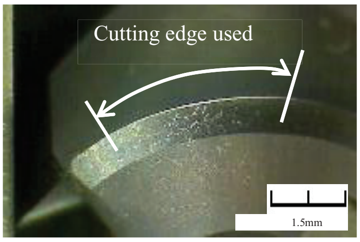


Fig. 9. Cutting edge with tool swing (α = 90 deg, ω = 0.25 deg)

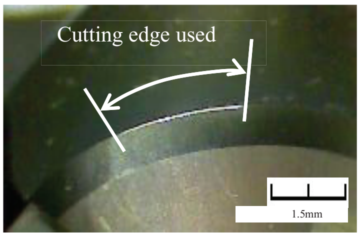


Fig. 10. Cutting edge without tool swing (α = 90 deg, ω = 0 deg)

4. Shape machining with tool swing

The above method is applied to the finishing process of metal molds, which have sculptured surfaces. As an example, a shape of metal mold is shown in Fig. 11. The tool path is generated on the workpiece surface as specified by an operator, and illustrated in the same figure [8]. At the time, collision between the tool and workpiece has to be taken into consideration in case of applying the tool swing method.

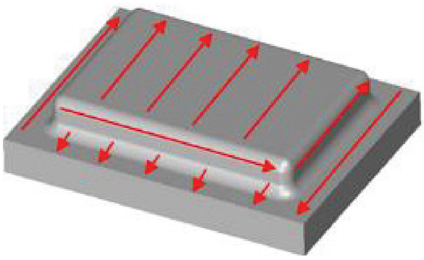


Fig. 11. Target shape and tool path

The tool path is divided into a number of division points Pi, where the normal vector **N** is generated. Then, the tangent vector is formed at every Pi, to be equal to the feed direction vector **F**. On the basis of these two vectors, **N** and **F**, the tool vector is determined by rotating **F** around **N** by 90 deg and then directing F upward within the plane between F and N by 60 deg, as illustrated in Fig. 12. The operation is carried out for all division points along the tool path. The center of the ball end mill is computed by offsetting from Pi in the direction of **N**, by the tool radius *r*. The CAM system to implement this method was written in Python [9].

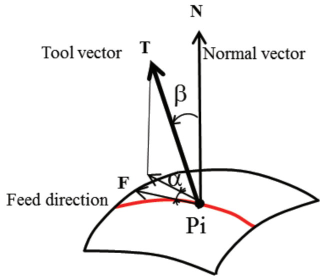


Fig. 12. Tool vector rotation

In machining experiments of the metal mold shape, the flank wear of the ball end mill and the surface roughness of the machined workpiece were measured in the same manner as the plane machining. The cutting conditions are shown in Table 4. The workpiece material is also SKD61.

Table 4 Machining conditions (No.2)

Tool : cemented carbide， AlCrN coating， φ10 mm， 2 flutes	
Workpiece : SKD61	Wet cutting
Spindle rev : 3000 rpm	Feed : 700 mm/min
Pickfeed : 0.5 mm	Depth of cut : 0.5 mm
Angle (α) = (90 deg)，Angle (β) = (15～45 deg，30 deg)	
Tool swing rate :ω = 0 deg/mm， 0.25 deg/mm	

Figure 13 shows the machined mold core workpiece. The average values of the flank wear and surface roughness were measured at the three surfaces①, ② and ③shown in Fig. 13. The machining order is from the surface ①, then to ② and finally to ③. As seen in Figure 14(a), the effect of tool swing to decrease tool wear is evident for all surfaces. However, with regard to the surface roughness there no noticeable difference observed for surfaces ① and ②, whereas a difference is noticeable for surface ③.The reason why there is a difference in surface roughness in the case of the surface 3 is considered to be that the influence on the surface surface also increases as the tool wear increases.

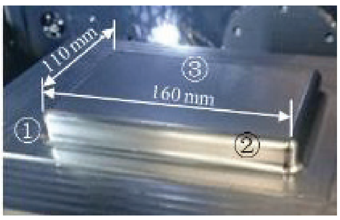
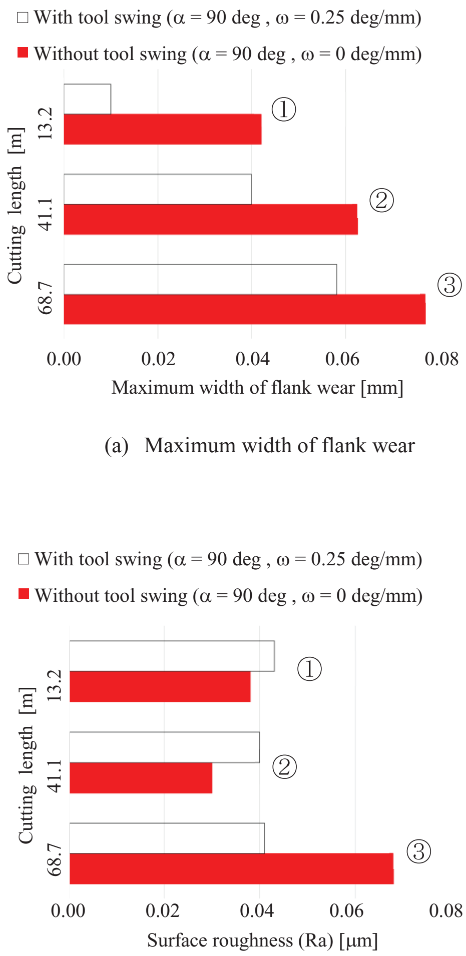


Fig. 13. Machined surface



(a) Maximum width of flank wear

(b) Surface roughness (Ra)

Fig. 14 Experimental results

5. Conclusion

This study proposed a method for decreasing tool wear by swinging the tool axis vector of a ball end mill, and can be summarized as follows:

(1) From the cutting experiments with plane, it was found that the surface roughness of workpiece is dependent on the tool axis inclination direction, and that there exists a most adequate direction.
(2) The machining method with the tool axis vector continuously swung allows for decreasing the tool wear due to dispersion across the tool surface.
(3) The proposed method can be applied to machining workpieces with sculptured surface.

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